# United States/European Union Co-ordination with HR Wallingford on Dredged Material Fate Modelling Improvements

**Final Report – April 2003**

**by**

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**London, England**

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## 13. ABSTRACT *(Maximum 200 Words)*

This is the Final report arising from co-operation between ERDC and HR Wallingford on the research of turbidity caused by dredging. It covers the period April 2001 – April 2003 with some additional information up to 1 August 2003. Details of the work are described in a series of 7 Interim Reports.

The work carried out over the two-year contract period consisted of:
- Six co-operation meetings held alternately in Europe and in the USA.
- Protocols for measurements, internationally reviewed and finally released on 1 August 2003
- Disaggregation Index study by WL Delft Hydraulics
- CFX Modelling
- Field Trial 1: grab dredger on R Tees
- Field Trial 2: trailing suction hopper dredger at Rotterdam
- An upgrade for TASS

Two papers were produced and presented at conferences and are included as appendixes in this report

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# Contract - Consultancy

The research project was set up to provide the basis of co-operation between ERDC (Waterways Experiment Station, Vicksburg) and HR Wallingford. Co-operation in the research reported in this document has been made possible through the support and sponsorship of the US Government through its European Research Office of the U.S. Army. This report is intended for the internal management use of the Contractor and the U.S. Government. The nominated representative for the US European Office is Mr Robert Kennedy. The responsible person at ERDC is Mr James Clausner. The Contract Number is N68171-01-M-5407.

The work being carried out by HR Wallingford was originally commissioned by VBKO, a consortium of Dutch dredging contractors together with the Rijkswaterstaat. The nominated representative for VBKO was Mr Hans Otten.

It has also been part funded by HR Wallingford's "in house" research funds.

Dredging Research Ltd also contributed to the work under subcontract to HR Wallingford. The nominated representative of DRL is Mr John Land.

The work was carried out under the project management of Mr Neville Burt in the HR Estuaries and Dredging Group. The work was carried out initially under HR Wallingford Job Number DAR 3024, then (due to internal management changes) subsequently transferred to DDR 3249.

Prepared by ..........................................................................................
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# Summary


United States/European Union Co-ordination with HR Wallingford on Dredged material fate modelling improvements

Final Report - April 2003

Report EX 4891
October 2003

This is the Final Report arising from co-operation between ERDC and HR Wallingford on the research of turbidity caused by dredging. It covers the period April 2001 – April 2003 with some additional information up to 1 August 2003.

The work that has been carried out has been described in a series of 7 Interim Reports, listed in Chapter 1.

The Dutch dredging industry and the Rijkswaterstaat, through VBKO, commissioned HRW and DRL to carry out new research to develop a calibrated software package which can be used to derive realistic estimates of sediment release. The object of the co-operation was to facilitate the collaboration of research being conducted by ERDC and HRW to measure total suspended solids (TSS) resulting from dredging and development of this software. It included exchange of data sets from field measurements and development of models for predicting TSS for a range of dredges, sediments, and hydrodynamic conditions (TASS). The pilot version had been developed in 1999.

ERDC has a number of models that predict nearfield TSS, though in most cases the models have been formulated and validated with older data collected with less-sophisticated instruments than are presently available. ERDC had considered improving these models, but HRW recently proposed to share the TASS models with ERDC, which appeared to be an excellent ERDC investment in light of the present high cost involved with collecting validation field data.

The work carried out over the two-year contract period consisted of:

- Six co-operation meetings held alternately in Europe and in the USA.
- Protocols for measurements, internationally reviewed and finally released on 1 August 2003
- Disaggregation Index study by WL Delft Hydraulics
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- Field Trial 2: trailing suction hopper dredger at Rotterdam
- An upgrade for TASS
- Preparation and presentation of two conference papers

# Contents

# 1. INTRODUCTION

Although this report officially covers the period to April 2003, due to some delays in organising payments etc the report has been delayed. It thus includes some additional information up to 1August 2003 to the extent that it is relevant to the general spirit of collaboration.

## 1.1 The issue

Both U.S. and European EU resource agencies are concerned about potential negative impacts associated with sediments suspended during dredging. Regulations on water quality relate to sediments suspended during the dredging process have been formulated, but have in most cases been based on little if any solid science. In many cases, the regulations are most likely much too conservative, but in some cases the opposite could be true. Both the Corps and various European EU agencies are continuing to fund research on measuring suspended solids resulting from dredging, and the corresponding development of models to predict suspended sediment concentrations in the area around the dredge. Due to the complexity of the problem, different types of dredges, a range of sediment types, and hydrodynamic conditions, it is exceedingly costly to investigate all the possible combinations. Collaboration of the two agencies performing the vast majority of research (US Army Engineer Research and Development Center (ERDC), and H. R. Wallingford (HRW) is an obvious method to maximise the amount and quality of research being conducted.

## 1.2 Research/Objectives

The objective of this research was to facilitate the collaboration of research being conducted by ERDC and HRW to measure total suspended solids (TSS) resulting from dredging and development of models to predict TSS from dredging. More precisely, the fundamental purpose of this research was for ERDC and HRW to co-ordinate their efforts to develop common methods of measuring TSS, exchange data sets from field measurements, and develop improved models for predicting TSS for a range of dredges, sediments, and hydrodynamic conditions. HRW is developing fully-calibrated computer models for predicting source strength (nearfield) TSS resulting from dredging. This modelling system is the Turbidity Assessment Software (TASS). HRW is collecting high-quality TSS data from a range of dredge types, sediment types, and hydrodynamic conditions. ERDC has a number of models that predict nearfield TSS, though in most cases the models have been formulated and validated with older data collected with less-sophisticated instruments than are presently available. ERDC had considered improving these models, but HRW recently proposed to share the TASS models with ERDC, which appeared to be an excellent ERDC investment in light of the present high cost involved with collecting validation field data.

## 1.3 Research Team

### In the USA

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Although not a party to the agreement, VBKO (Vereniging Van Waterbouwers in Bagger-Kust Oeverwerken) is the client for much of the work being undertaken by HR Wallingford. Hans Otten is the Chairman of the Steering Group for VBKO. It was agreed by WES and HRW that Mr Otten should be invited to attend the co-operation meetings.

## 1.4 Reports

A series of Interim Reports has been produced as follows:

1st Interim Report – May 2001 (HR Report EX 4702)
2nd Interim Report – August 2001 (HR Report EX 4703)
3rd Interim Report – November 2001 (HR Report EX 4704)
4th Interim Report – Februay 2002 (HR Report EX 4705)
5th Interim Report – May 2002 (HR Report EX 4706)
6th Interim Report – August 2002 (HR Report EX 4707)
7th Interim Report – November 2002 (HR Report EX 4884)

## 1.5 Meetings

Co-operation meetings have been held from time to time throughout the project.

| | | |
|---|---|---|
| Meeting 1 | HR Wallingford | May 2001 |
| Meeting 2 | WES Vicksburg | June 2001 |
| Meeting 3 | Gouda, Netherlands | November 2001 |
| Meeting 4 | WES Vicksburg | April 2002 |
| Meeting 5 | Washington DC | January 2003 |

Reports of Meetings 1 – 4 are given in the Interim Reports.

Meeting 5 was a special meeting organised by Dr Clausner in Washington and included representatives from many organisations in the US and some from Europe, including the project team. Since it took place subsequent to the 7th Interim Report an account, produced by Dr Clausner, is attached to this report as Appendix 1.

# 2. WORK CARRIED OUT BETWEEN NOVEMBER 2002 AND APRIL 2003

## 2.1 Completion of TASS Phase 2 Track 2 - ISCOT

**The models**

Following submission of the reports to VBKO the committee provided some comments. These concerned the type of draghead and the pressure differences used in the CFX modelling

It was our main concern to see if it is possible to use CFX modelling as a way of improving the draghead term in TASS and as a partial substitute for the Disaggregation Index. The conclusions are very clear that the re-suspension caused by the hydraulic erosion process induced by the draghead is very small and that the bulldozing effect is likely to be much more significant. This would apply whether the draghead is only partly in the bed or totally submerged in it. In fact, in the case of a totally submerged draghead operating in silt it is hard to imagine how resuspension by hydraulic erosion can take place in the immediate vicinity of the draghead, and in such a way that material is released into the water column, because the surrounding medium will be of such a high density. In this case the bulldozing effect will again be the dominant process. The difference in this case is that the bulldozer itself is submerged.

It is not proposed to do further work on CFX modelling of the draghead under the present ISCOT contract. Further refinements can be made in Phase 3 or as work progresses through other sources of funding.

**Use of TASS**

Interface software to enable use on standard PC under Windows 98 or higher was purchased and is installed.

The short user-guide for TASS has not yet been produced. This is aimed at the level of users with a good knowledge of dredging.

**Distribution of TASS**

Before it is distributed a suitable method must be found to make the algorithms secure from interference or theft.

## 2.2 Completion of TASS Phase 2 Track 1 – Protocols

### 2.2.1 International review

Meetings were held with the last three nominated reviewers in December 2002, de Vlieger (Belgium), van Raalte (Netherlands) and Jensen (Denmark). The port authority of Hamburg was also added (Netzband). A full set of notes was prepared on all of the reviews received. In addition many comments were made verbally and noted directly onto a master copy held by HR Wallingford.

As a result of the comments and in the light of experience of the two trials so far conducted it was thought best to do a major re-write. It was also felt that the document will be circulated widely and the importance and quality of the TASS project will be judged on the quality of the Protocol. The new version has thus been given a very professional look making use of text boxes, colour highlighting of headings and many photographs.

A number of copies and a disk version has been supplied to ERDC.

## 3. SUMMARY OF FINDINGS FROM THE RESEARCH

The Dutch dredging industry and the Rijkswaterstaat, through VBKO, recognised the need to improve this situation and commissioned new research to develop a calibrated software package which can be used to derive realistic estimates of sediment release.

### 3.1 TASS Mk1

Phase 1 of the work, comprised a review of previous research then the production of a pilot version of the software. This had been completed in 1999.

TASS (Turbidity Assessment Software) is the name given to the models being produced. It has four main components:

1. A soil model which describes the tendency for soil and rock to disaggregate during the dredging process;
2. A suite of process models which, in combination with the soil model, describe the rates and locations of sediment release, and the particle size distribution of the released sediment;
3. A dynamic plume model which describes the initial behaviour of the sediment suspension; and,
4. A database.

The process models predict the release of sediment from grab, cutter suction, bucket ladder, backhoe and trailer dredgers. These have been selected because they are the most commonly-used dredgers but additional types may be added in the future.

Output from the process models is used as input to the dynamic plume model which predicts the initial behaviour of the material released from the dredger during the dynamic phase of dispersion, i.e. up to the point at which further sediment transport is dominated by the processes of advection and settling. The behaviour of the sediment after this point is not covered by the system as there are several existing proprietary passive sediment transport models such as SSFATE which can be applied to this stage of plume development.

### 3.2 Protocols for measurements

Phase 2 commenced in January 2000. Phase 2 consisted of two main elements. The first was the development of an internationally accepted protocol for measuring turbidity during dredging operations. This transpired to be a lengthy process and involved producing several versions. The Protocol was reviewed by representative organisations from:

USA
UK
Netherlands
Belgium
France
Germany
Denmark

The experts carrying out the review represented regulating authorities, dredging contractors, researchers and port engineers.

The final version was released following the period of contract here reported on 1 August 2003.

## 3.3 Disaggregation Index

The second part of Phase 2 was the development of a test method to determine a parameter which will represent the degree to which a sediment breaks down (disaggregates) when subjected to the forces of dredging. The disaggregation test work was carried out by Delft Hydraulics. They concluded that a meaningful test would be difficult to create due to problems of scale and recommended a more theoretical approach. Not all agreed with this however it was agreed to investigate the use of CFX modelling to develop an erosion function that could be included in TASS.

## 3.4 CFX Modelling

The CFX modelling approach was applied as a test case to the trailing suction hopper dredger draghead term. It proved to be effective in determining the turbulent kinetic energy around the two types of draghead tested, the California draghead and the IHC silt draghead.

The method used to evaluate the effect of that turbulence on erosion was based on well established erosion formulae based on previous work by HR and other researchers. It was used to estimate rates of erosion for sand and for mud. When tested this produced the surprising result that rates of release for mud were much lower than for sand. However, on closer inspection, the explanation was obvious: most of the sand would be re-suspended to only a few mm above the bed and would settle again in a short distance from the draghead and would not contribute to the plume. With this taken into account the rates of release for sand appear to be of the same order as the (fairly limited) available observations in the field.

The rates of release for mud, however, are much lower than field observations would suggest. The reason hypothesised for this is that there is a “bulldozing” effect of the draghead, particularly when operating with the IHC silthead in mud.

The CFX model appears to be a useful tool for examining the turbulence arising from dredging activity and it is recommended that it could be used to improve other process models in TASS. As regards the cutter suction dredger model, we have become aware of more literature on the modelling of the hydraulic processes affecting release around this type of dredger and would wish to review that before recommending any CFX modelling of it.

We remain convinced that the most significant advances at this stage in the work will derive from obtaining more field calibration data. This will give a more detailed and reliable understanding of the processes taking place and will provide much needed empirical coefficients that will ensure that the models are giving reasonable results.

It is also our opinion that the original concept of a Disaggregation Index should be considered again. There is clearly a need for some improvement in the way this is presently incorporated in TASS.

## 3.5 Field trials

Phase 2 included a limited number of field trials to test the protocols and obtain initial calibration data.

### Tees trial

The first of these, a grab dredger working on the River Tees in England, was completed in April 2000. A full report was produced and a copy given to ERDC (confidential - not for general release). A summary report for general release was also produced and has been given wide distribution.

### Rotterdam trial

A brief initial account was given in the 6th Interim Report. The data is still being processed and no additional reporting has yet taken place. The indications are that the results are of good quality and show some interesting features.

## 3.6 An upgrade for TASS

Also as part of Phase 2 it was decided to upgrade TASS. The main items were:

- Debugging the Mk 1 version
- Improving some of the formulations used
- Inclusion of the dynamic plume model
- Full range of sensitivity tests on all of the TASS process models.

The new version, styled TASS Mk2.1 with dpm was given to VBKO for testing and approval in June 2003.

## 4. PUBLICATIONS AND TECHNICAL REPORTS ARISING FROM THE RESEARCH

In addition to the formal reports to VBKO (which are confidential to the client) two papers describing the co-operation have been produced and presented at conferences.

Burt TN and Clausner J (2002). US-European co-operation on turbidity measurement and prediction. Proc. “Dredging 02”, ASCE’s third specialty conference on dredging and dredged material disposal. Orlando, 5 – 8 May 2002.

Burt TN and Hayes DF (2003). US-UK Co-operation on dredging turbidity modelling. Proceedings of the Western Dredging Association Twentieth Technical Conference (WEDA XXIII) and Thirty-Fifth Annual Texas A&M Dredging Seminar (TAMU 35), Chicago, Illinois, USA June 10 – 13, 2003.

Copies of these papers are given in Appendixes 2,and 3.

## 5. CONCLUDING REMARKS

It is the opinion of the HR/DRL team that co-operation with ERDC has been a very instructive and fruitful exercise for all parties. Our client VBKO has also valued the co-operation particularly with regard to the discussions and dissemination of the protocols and the general philosophy of the project.

Although final solutions to this problem still seem to be some years away nevertheless significant progress has been made in the two year period of this project.

It is to be hoped that further co-operation will continue in this important area of work.

## 6. ACKNOWLEDGEMENTS

The HR/DRL team wish to acknowledge the spirit of co-operation, enthusiastic involvement in discussions and active participation in this project of the staff of ERDC, Vicksburg. In particular, the commitment of Jim Clausner during a period when his wife has been undergoing prolonged medical treatment for a life-threatening condition has been quite outstanding.

We also wish to acknowledge the technical contribution of Dr Don Hayes of Utah University who spent time at HR Wallingford on this project while on sabbatical in the academic year from October 2002 – September 2003. Dr Hayes is a leading expert in this field in the USA and the opportunity for long discussions on difficult technical matters has been much appreciated.

Finally we wish to acknowledge the London Office of the Corps of Engineers and thank them for undertaking the difficult task of administering this contract. The personal interest of Jerry Comati and latterly his replacement Bob Kennedy has helped to keep the project as a whole on track.

# *Appendices*

# *Appendix 1*

Summary of Washington DC Meeting - January 2003

## Appendix 1 Summary of Washington DC Meeting - January 2003

Prepared by James Clausner

**Summary**
**Resuspension Due to Dredging Workshop**
**22 January 2003**

1. On January 22, 2003, the US Army Engineer Research and Development Center's (ERDC) Coastal and Hydraulics Laboratory (CHL) and Environmental Laboratory (EL) hosted a one-day workshop on resuspension of sediments due to dredging. The workshop was held at the Dulles Airport Embassy Suites Hotel outside of Washington, DC. Resuspension of sediments during dredging has been and continues to be a topic of considerable interest to the US Army Corps of Engineers (USACE), US Environmental Protection Agency (EPA), the Department of the Interior's Minerals Management Service (MMS), state resource agencies, and others because of potential negative impacts to the biological community or aesthetic reasons. Resuspension of sediments is a concern during maintenance dredging, mining of sand for beach nourishment, and particularly during clean-up dredging of contaminated sediments. The need to develop good quality models for predicting resuspension due to dredging that will allow agencies to base regulations controlling dredging on good science has long been recognized in the United States. The USACE has funded research on resuspension during dredging since the 1970s, and recently MMS has begun to fund research on this topic. Dutch dredging contractors (VBKO) and the Dutch government (Rijkswaterstaat) are also funding research on resuspension. Other European counties are showing considerable interest in accurate predictions of resuspension due to dredging as a basis for sound regulatory policy. EPA has funded some research on resuspension of contaminants during clean-up dredging and continues to fund research on desportion of contaminants from sediment particles.

2. The purpose of the workshop was to allow the USACE, EPA, MMS, Rijkswaterstaat, and their collaborating partners to learn the history, goals, status, and plans of each group's research efforts. Recent efforts have focused on improving plume measurement techniques, developing models for predicting resuspension at the dredge and software that displays the features of the far-field resuspension plume. Twenty-six persons attended the meeting including representatives from EL and CHL, USACE HQ, EPA HQ, EPA's Narragansett and Cincinnati Laboratories, the Rijkswaterstaat, HR Wallingford and Dredging Research Limited, the University of Utah, Louisiana State University, Applied Science Associates, Baird & Associates, Ltd., and Coastal Hydraulics and Transport.

3. After an introduction and welcome by Dr. Robert Engler (EL), Dr. Don Hayes (University of Utah) gave an overview on resuspension due to dredging. Pertinent points made during this overview were:
   a) Scientists have a reasonable feel for the significance and extent of dredging induced sediment resuspension. Good quality available data sets are quite limited. There have been a number of dispersed efforts but to date they have been hampered by lack of a long-range objectives, budget limitations, regulatory confusion, and self-serving interests.
   b) Advancing the science will require clear problem definition; focus on long-term goals and desired outcomes, an interdisciplinary and multi-agency approach, a carefully constructed research plan and substantial, persistent funding. Dr. Hayes described the four spatial scales associated with transport of resuspended sediment and the temporal scales.
   c) Performance criteria and regulatory controls associated with dredging induced resuspension must balance productivity (project duration) with allowable water quality impacts. The criteria and controls should be based on science, not conjecture. Available data are limited, which

leads to overly protective regulations in most cases. Improved data and models should equal a better regulatory framework. Resuspension of sediments due to dredging is difficult to measure with sufficient quality to allow use of the data for model development. The variety of dredges, operating variables and operator skill, hydrodynamics, and sediment characteristics greatly complicate developing robust models. Based on work in the 1970s, 80s and 90s, some empirical techniques were developed, but extrapolating these techniques to other dredges, sediments, environments, has proven to be problematic. Similarly, some simple models were developed during the same time frame, but they have been shown to be inadequate in many situations. In many cases, particularly with mechanical dredges, the resuspension plume is very aperiodic and generally never reaches a steady state.

4. Following Dr. Hayes overview, agency viewpoints on resuspension due to dredging were presented:

a) Mr. Clausner described the USACE history of resuspension research, with a considerable effort in the 1980s on measuring resuspension from a range of dredge types focused mainly on maintenance dredging of clean sediments. Mr. Clausner also briefly described research on resuspension due to vessel passage. Finally, Mr. Clausner described resuspension research being done under the Corps Dredging Operations and Environmental Research (DOER) program including development of the Suspended Sediment FATE of dredged material model (SSFATE).

b) Dr. Burt described European perspective, including the problems associated with having regulations associated with resuspension due to dredging not based on sound science. The solution is to have good models for predicting resuspension. The weak link in developing models for predicting resuspension has been measurement of source strength. HR Wallingford and Dredging Research Limited (DRL) are now developing improved predictive models, which require high quality measurements of source strength. The USACE is collaborating on this research through the DOER program.

c) Dr. Burt noted that as part of their contract with VBKO (consortium of Dutch dredging contractors) and the Rijkswaterstaat, HR Wallingford and DRL have developed a draft set of protocols for collecting high quality resuspension data that can be used to improve predictive models. These protocols and monitoring tools and techniques have been tested on a bucket dredging project and a hopper dredging project. Dr. Burt has had a number of representatives from European countries review the protocols. The reaction to the protocols and their purpose, to develop good science for accurately predicting resuspension that will lead to sound regulations, has been quite positive. DRL will shortly begin the process of rewriting the protocols to take into account review comments and experience gained during the three dredging resuspension measurement field tests. A revised set of protocols is expected in March 2003.Mr. Otten from the Rijkswaterstaat provided the Dutch government perspective. The Dutch government does not have general standards for resuspension; they believe resuspension will be quite site specific. He acknowledged that detailed knowledge of resuspension source terms is lacking, as are the related models. Without this information, there is no way to predict or control resuspension. Without this scientifically sound base of information, the Dutch government is not in a position to set standards the dredging industry has to comply with. That is why they joined their dredging industry (VBKO) on the TASS project. This project aims at setting up a publicly available model with certain predictive values for the rate of release of sediments caused by dredging.

e) Mr. Drucker described work MMS is doing to determine environmental impacts associated with hopper dredging of aggregates. Much of this research has been done in conjunction with HR Wallingford and other British companies. Great Britain uses hopper dredges to mine 30% of their aggregates.Dr. Ells provided a short introduction on EPA's research needs including prediction of resuspension of contaminated sediment during clean-up dredging; prediction of water column dissolved and particulate contaminant concentrations and their impact on biota, and the efficacy of silt screens to control resuspension over a range of conditions. Dr. Nelson

described measurement of resuspension on the New Bedford Harbor superfund clean-up project.

5. The second set of presentations focused on recently developed tools, primarily models, for predicting resuspension and displaying results and techniques for measuring resuspension.

   a) In his presentation on dredging source terms, Dr. Hayes described a change in terminology. He described a zone immediately around the dredge head that includes mixing induced by the movement of the head, and suggested (after some discussion) this region be called the zone of initial dilution (ZID). Dr. Hayes described problems with resuspension data sets, problems with the TGU method, the resuspension factor approach, empirical methods, transient modeling and its implications, and a table describing modeling complexity. Through the Corps' DOER Program, Dr. Hayes is being funded to develop an improved matrix of basic resuspension factors that can be used as source strength input by models like SSFATE. These factors will take the basic resuspension rate and modify it to account for factors such as cycle time (production rate), bucket size, adjustments for sediment properties, etc.
   b) Mr. Eric Anderson of Applied Science Associates (ASA), described the Suspended Sediment FATE of dredged material model (SSFATE). SSFATE was developed initially developed under contract by ASA under the USACE DOER Program to provide a tool for biologists to show the extent of a plume and allow them to negotiate environmental windows with state regulators. SSFATE's source terms are based on older algorithms, but it has advanced and easy to use plume tracking and display capabilities. Plans are to allow improved source strength models to be easily incorporated into SSFATE, along with other improvements. Dr. Gailani presented a sophisticated application of SSFATE where it was used to predict impacts of mixed sediments placed in the nearshore off Tybee Island, GA.
   c) In his presentation, Dr. Burt noted an improved version of the Turbidity Assessment Software (TASS) being developed by HR Wallingford and DRL has now been completed. TASS includes a complete analysis of the dredging processes, and originally planned to look at all five types of dredges. Initial efforts focused on the grab (mechanical) dredge. Recently, work has focused on trailing suction hopper dredges. Future efforts include more work on the bulldozing effect of the draghead and additional field measurements.
   d) John Land (DRL) discussed field calibration of TASS based the resuspension plume measurements. The objectives were to measure all the sediments released, establish a "characteristic release rate," quantify release from different stages of the dredging process and relate the rate of sediment release to the dredging process (soil, dredge type, manner of operation, etc.). Mr. Land noted the following characteristics of dredge plumes: concentrations are extremely variable; the plumes may small (< 10 m wide close to the dredge); temporally very variable/intermittent; and sediment may settle quickly to the bed. Mr. Land discussed consequences for release measurement, then went on to describe the primary methods for measuring plumes for all dredges except trailing suction hopper dredges and then for trailing suction hopper dredges. Included were results from a number of projects including the Tees River, where measurements on a mechanical dredging operation were repeated to determine the effect of air entrainment on measurements.
   e) Based on Dr. Hayes and John Land's presentations, Mr. Clausner developed the following discussion. Tools, techniques, and protocols for making good quality measurements have been lacking in the past. Improvements are being made; particularly the use of ADCPs (combined with high quality software for converting acoustic backscatter to total suspended solids) combined with OBS gage readings and ground truthed with TSS measurements from water samples. ADCPs allow the closely spaced TSS measurements needed for model development. Near field collection of resuspension data using OBS gages and water samples has been demonstrated for bucket and cutterhead dredges. However, safely operating around working dredges of most types continues to be dangerous. Collecting data of sufficient quality has been and will continue to be quite expensive in most cases. Basic definitions of sediment loss, and the spatial and temporal limits on which to define loss have not yet been widely accepted.

f) Mr. Douglass Scott from Baird and Associates, Ltd., described a model they are developing under contract to MMS for predicting the resuspension plume and sedimentation characteristics associated with trailing suction hopper dredges mining aggregates and beach quality sand from US Federal Waters. In addition to Baird & Associates, the development team includes HR Wallingford (plume model development and testing), DRL (dredging process algorithms), Coastline Surveys Limited (monitoring data for model evaluation), and Marine Ecological Survey, Ltd (Dredging impacts). Dredging operations source terms include TSS associated with overflow and the drag head. The model performance evaluation is now in progress as is sensitivity testing and model adjustment.

6. Under sponsorship by EPA and the Corps, the Hazardous Substances Research Center (HRSC) Southwest located has been investigating desportion of contaminants from sediment particles. Dr. Thibodeaux of LSU summarized the current research. The “Hockey Stick” desportion model for chemical solubilization from suspended particles is a simple mathematical algorithm that describes the behavior of contaminant release from sediment particles. This algorithm can be applied to PAHs, other hydrocarbons, PCBs, chlorinated solvents, pesticides and metals (eventually). Research has shown that the loosely bound contaminants, the larger amount of the chemical mass, are released rapidly (hours), while the more tightly bound contaminants are released much more slowly. A plot of the release amount vs time resembles a hockey stick.

7. Dr. Douglas Clarke (EL) described some recent and upcoming efforts to collect resuspension data on USACE dredging projects. The majority of the discussion focused on the upcoming dredging of the Providence River in Rhode Island.

8. Following the formal presentations, an open discussion of possible collaborations on future research was conducted. Pertinent points are provided in the following paragraphs. There was a strong consensus to continue coordination and collaborative efforts. EPA HQ has agreed to fully cooperate in this effort on resuspension.

9. At the conclusion of the meeting Bob Engler directed James Clausner and Douglas Clarke to develop a framework that describes research needed, priorities, and some idea of costs. Contaminant loss issues, and associated models (as described by Dr. Thibodeaux will be considered). Drs. Burt and Hayes have volunteered to make a first cut at this framework. This framework will be provided to DOER, upper Corps and EPA management to assist in identifying and setting priorities for future research.

10. The following is an action list of specific coordination items.

a) Mr. Clausner will provide a web site address that has a copy of all the presentations from the workshop.
b) Additional notes from the meeting taken by Mr. Clausner will be provided to participants.
c) After HRW/DRL completes the next update of the protocols they will be provided to EPA for review/use.
d) There is a potential for coordination between ERDC, NED and EPA on future dredging of New Bedford Harbor.
e) Mr. Drucker will provide Mr. Clausner with a copy of the resuspension model from hopper dredges developed by Baird and Associates, LTD.
f) ERDC and HR Wallingford are planning to sponsor meeting in Europe in the fall of 2003 to request wider European support in the development of protocols, data collection and model development for resuspension due to dredging.
g) Mr. Joe Wilson, HQ USACE, requested that some calculations be made to put resuspension due to dredging in perspective with the amount of resuspension due to storms.

# Appendix 2

Paper presented at Dredging 02, Orlando

## Appendix 2 Paper presented at Dredging 02, Orlando

Us-European Co-Operation on Turbidity Measurement and Prediction

### US-EUROPEAN CO-OPERATION ON TURBIDITY MEASUREMENT AND PREDICTION

Neville Burt BSc, CEng, MICE[1], James Clausner[2]

**Abstract:** The measurement and prediction of turbidity caused by dredging and its effects on the aquatic environment have become major issues affecting dredging projects world-wide. Until recently European and US organisations have been working separately on the problem.

In the US, resource agency concerns over turbidity and other dredging related impacts result in the imposition of "Environmental Windows", limited periods during the year when dredging is allowed. In many US locations, "Seasonal Restrictions," periods during the year when dredging is not allowed because of suspected (as opposed to proven) environmental impacts, greatly restrict dredging and increase costs. This was a major topic of discussion at the National Academy of Sciences (NAS) Workshop on Environmental Windows (Washington, D.C. May 2001). Recognising that these matters are being discussed internationally the NAS invited the principal author to participate in the workshop and bring a European perspective. The U.S. Army Corps of Engineers Dredging Operations and Environmental Research (DOER) programme is sponsoring a variety of work to quantify the biological impacts related to dredging and disposal in the marine environment. A key product of the DOER Environmental Windows Focus Area is the Suspended Sediment FATE of dredged material software (SSFATE), which predicts the movement of the suspended sediment plume during a dredging operation. The use of GIS type overlay systems provide high quality dynamic visualisations of the plume.

In Europe the problem has presented itself more in the context of restrictions and turbidity standards placed on dredging contracts. These restrictions can also occur in any part of the world where the major dredging contractors operate. The debate as to whether or not the standards are reasonable and achievable, or even whether they are actually measurable, still continues. Recognising that this issue will only be resolved by a proper scientific approach to measurement and prediction, a consortium of Dutch Dredging Contractors and the Dutch regulating authority, the Rijkswaterstaat, commissioned HR Wallingford, the UK's national hydraulics laboratory, in association with Dredging Research Limited, to produce validated software for prediction of turbidity caused by various types of dredging operation

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(Turbidity Assessment Software (TASS)). The initial focus has been on describing and modelling the initial generation of suspended sediment. Pilot software has been produced and is currently being refined.

Initial discussions between the European and US organisations have shown common recognition and appreciation of the technical problems involved. Furthermore there is mutual recognition of the need for international co-operation in order to obtain sufficient good quality calibration data covering the range of type of dredger, soil conditions and hydrodynamic conditions.

The paper will outline the approaches being adopted in Europe and in the USA and how it is hoped that they will merge to give a high quality, reliable tool for use by dredging people and regulators alike. The paper highlights the technical problems such as dynamic measurement of plumes, and processes of sediment disaggregation and entrainment. It will also show how these problems are being tackled.

## INTRODUCTION

The purpose of this paper is to inform delegates to the conference and readers of the proceedings about the co-operation that is currently taking place between the US Army Corps of Engineers Dredging Operations and Environmental Research (DOER) programme and a research programme being funded by VBKO and the Rijkswaterstaat in the Netherlands. VBKO is a consortium of Dutch dredging contractors, concerned that regulation of dredging operations should be based on sound knowledge of actual impacts. The research in Europe is being carried out by the UK's national hydraulics laboratory (HR Wallingford) and a private company, Dredging Research Ltd (DRL). The research in question in both the US and in Europe is concerned with turbidity caused by dredging.

The paper is divided into four main sections, a description of the problems associated with turbidity, a discussion about the solutions being adopted, a description of the development of predictive software and finally how it is intended to calibrate the software so as to increase the confidence of both regulators and dredging organisations.

At the outset of this paper it is vital to differentiate between turbidity and suspended solids concentration. Turbidity is a measure of the light obstruction caused by sediment in the water. For any given suspended solids concentration the turbidity varies enormously depending on the particle size distribution of the sediment. A high concentration of sand may have a very low turbidity while a very low concentration of fine silt may have a very high turbidity. There have been examples where plumes arising from dredging have been clearly visible from aircraft but the suspended solids concentration has been near or below the detection limit of conventional equipment. The focus of the research described here is on sediment release rather than on strictly defined turbidity.

## PROBLEMS ASSOCIATED WITH TURBIDITY

The problems associated with turbidity may be considered to be the actual impacts and the perceived potential impacts. In the case of actual impacts it is important to be able to predict what they are so that an informed evaluation can be made regarding a proposed dredging operation. In the case of perceived potential impacts the "precautionary approach" will often be applied and result in control measures which may or may not be necessary but will almost certainly be expensive. In both cases the only sensible way forward would seem to be an improved understanding of the processes and impacts and better predictive capability.

### Impacts

Sediment plumes arising from dredging operations are perceived by many stakeholders in the marine and coastal environment to cause environmental effects that require investigation and monitoring. The

dredging may be undertaken for any one of a number of reasons, such as the extraction of marine aggregates for construction, to gain material for beach recharge, to deepen waterways as part of capital works or for the maintenance of berths and navigation channels and, less often, to 'clean-up' contaminated water bodies. The dredging industry and government agencies have, therefore, undertaken or commissioned a number of research studies into the potential impacts of sediment plumes. Research has also been commissioned into the different sediment plumes that arise from dredging different materials using different dredging techniques. However, although considerable progress has been made on the mathematical modelling of sediment plumes and on the field measurement of plumes using acoustic and optical techniques, supported by on-site sampling and calibration, there is a lack of verified predictive techniques and a lack of knowledge of the environmental effects of sediment plumes.

Under current UK legislation, all dredging licence applications and some maintenance dredging operations are subject to Environmental Impact Assessment (EIA). All EIAs include extensive consultation with stakeholders, including the regulators, conservation agencies and fishery organisations, and most assessments include a review of the potential impacts arising from the generation of sediment plumes. Specifically, assessments tend to investigate the environmental effects associated with the sediment plume while it is in the water column and its subsequent settlement to the seabed.

During these phases, sediment plumes have the potential to affect various environmental parameters. Water quality can be impacted, for example, by increasing the biological oxygen demand of the water column or releasing previously bound-up contaminants. Marine ecology, both on the seabed and in the water column, can be affected due to physical processes such as shading or smothering. Shellfisheries can also potentially be impacted by sediment plumes as a result of effects on their filter-feeding efficiency. Similarly, impacts on fisheries can arise due to the physical alteration of spawning and nursery areas and direct physiological impacts on juvenile and adult fish (John et al 2000).

In the US, resource agency concerns over turbidity and other dredging related impacts result in the imposition of "Environmental Windows", limited periods during the year when dredging is allowed. In many US locations, "Seasonal Restrictions," periods during the year when dredging is not allowed because of suspected (as opposed to proven) environmental impacts, greatly restrict dredging and increase costs. This was a major topic of discussion at the National Academy of Sciences (NAS) Workshop on Environmental Windows in Washington, D.C. in May 2001. Recognising that these matters are being discussed internationally the NAS invited the principal author to participate in the workshop and bring a European perspective. The report has just been released (National Academy, 2002). One of the key recommendations of the workshop was that all existing scientific data and information should be exploited in evaluating and setting windows as part of an overall management strategy for dredging and disposal operations.

## Measurement

One of the biggest problems associated with improved understanding is the actual measurement of turbidity. In order to obtain the scientific data (as recommended by the National Academy) it is essential to have reliable methods of measurement and meaningful strategies for obtaining the measurements. Two types of measurement are required, one concerning the impact and the other concerning the turbidity (or suspended solids concentration) itself. Both are still at early stages of development and as a result the precautionary approach is applied. There is an implicit assumption that turbidity is bad for the environment. Whilst in some cases this may be true in others it may not be true. If turbidity does have an impact it is essential to be able to measure the turbidity and the impact in order to be able to correlate the two.

The principal author has come across many instances where turbidity standards have been set (e.g. "turbidity shall not exceed 50ppm above background concentration") without any definition of:

- how, when or where the restriction applies;
- how it is to be measured; or
- what the background concentration is or how it is to be established.

It would also seem to be the case that there is little or no knowledge of what impact will occur if the value is exceeded.

It is clear that a first step in finding solutions is a better description of what is happening in terms of sediment release when a dredger is working. That means a combination of field measurements and predictive modelling.

## SOLUTIONS

The U.S. Army Corps of Engineers Dredging Operations and Environmental Research (DOER) programme is sponsoring a variety of work to quantify the biological impacts related to dredging and disposal in the marine environment. A key product of the DOER Environmental Windows Focus Area is the Suspended Sediment FATE of dredged material software (SSFATE), which predicts the movement of the suspended sediment plume during a dredging operation. The use of GIS type overlay systems provide high quality dynamic visualisations of the plume.

The Dutch dredging industry, through VBKO (Vereniging van Waterbouwers in Bagger-, Kust en Oeverwerken), has commissioned new research with the objective of producing a software package which can be used with reasonable confidence by all parties, including the regulators and the industry alike, to predict sediment release during dredging and disposal (HR Wallingford 1999).

The research has sought to identify all of the mechanisms by which sediment is released during dredging and to develop models that predict the rates of release. Use has been made of previous research efforts in this field, particularly work undertaken by the Corps of Engineers in the USA (Collins 1995) and by several Netherlands organisations including the Dredging Research Association (CSB). In some cases, predictive models already exist (e.g. overflow losses from trailer dredgers) but, in most, little theoretical work has been done. In all cases, accurate field measurements of losses are not available although some measurements are available which can be used to derive an initial ‘order of magnitude’ calibration.

The software, known as TASS, predicts sediment release, and the initial dynamic behaviour of the sediment plumes, in a logical manner and in broad agreement with the sparse field data. Future work will focus on obtaining accurate field measurements of sediment release, using conventional and innovative methods, in order to calibrate and refine the predictive components of the software package.

The TASS initiative was first presented in the USA in June 2000 (Burt et al, 2000). A brief summary of the structure is given below.

## TASS

The pilot version of TASS had four main components:

- A soil model which describes the tendency for soil and rock to disaggregate during the dredging process;
- A suite of process models which, in combination with the soil model, describe the rates and locations of sediment release, and the particle size distribution of the released sediment;
- A dynamic plume model which describes the initial behaviour of the sediment suspension; and,
- A database.

The process models predict the release of sediment from grab, cutter suction, bucket ladder, backhoe and trailer dredgers. These have been selected because they are the most commonly-used dredgers but additional types may be added in the future.

Output from the process models is used as input to the dynamic plume model which predicts the initial behaviour of the material released from the dredger during the dynamic phase of dispersion, i.e. up to the point at which further sediment transport is dominated by the processes of advection and settling. The behaviour of the sediment after this point is not covered by the system, as there are several existing proprietary passive sediment transport models that can be applied to this stage of plume development.

The database is used to store details of field measurements of sediment release around working dredgers. The database will be accessible using a range of search routines and will include facilities to extract and analyse data in a manner that will enable the predictive models to be refined as measurements accumulate.

**The soil model**

The soil model comprised a disaggregation index (DI) that described the extent to which the soil or rock tends to disaggregate (i.e. release sediment) during the dredging process; and a function which defined the particle size distribution of the released sediment.

The disaggregation index was based on geotechnical properties that are commonly measured during ground investigations for dredging works. Further development work on the DI has since been carried out and has resulted in a different approach being adopted. It was felt that the concept of a DI was flawed because it did not fully represent the hydraulic forces that impact a sediment under process of dredging. In the new approach there will be three components to model the process of entrainment by erosion:

A. A hydrodynamic model (CFX) that gives the flow/turbulence field in detail around the various components of the dredger, for example the draghead of a trailing suction hopper dredger;
B. A function that describes the properties of the sediment relevant to its potential erosion and how those properties may be changed from the "in situ" properties (the ones normally measured).
C. An erosion function that relates the output of the hydrodynamic model to entrainment rates;

**The process models**

The amount of sediment that is lost will depend on the type of dredger that is being used, its size and the manner in which it is operated. These aspects are incorporated in the process models. The models define the sediment release in terms of rate of release (in kg/s) and the points of release or relative distribution of the release through the water column.

The output of the process models will be used as input data to the dynamic and/or passive (as appropriate) sediment plume models. The process models do not include any functions describing the environment into which the sediment is released, e.g. the current regime, water chemistry and temperature, because these do not greatly influence the instantaneous rate of release. The one exception to this rule is loss of sediment from the freshly-dredged surface, which depends on a combination of water currents, soil properties, the degree of disturbance of the dredged surface and spillage of material during dredging.

At this stage, all the process models, except for the trailer dredger, have deliberately been kept simple. The approach has been to identify those components of the dredging geometry and processes which, on the basis of logical assessment, are likely to most influence the release of sediment. It is recognised that, in some cases, the models may need to be developed in a more complex form in the future but, at this stage, the available field measurement data are inadequate to justify the development of complex models incorporating all of the operating parameters which might influence sediment release rates.

## The dynamic plume model

A key characteristic of sediment plumes released during dredging and disposal operations is that the sediment laden water has a higher density than the ambient water and hence tends to sink. This type of behaviour can be described as a negatively buoyant plume. In some cases, as in the overflow from a trailer dredger, or disposal from a split hopper barge, the sediment-water mixture enters the surrounding water with some initial momentum but it is mainly the density contrast between the released mixture and the surrounding water which dominates the behaviour.

As the sediment plume sinks, turbulence at the edge of the plume leads to entrainment or mixing of the ambient water into the plume, leading to expansion and dilution of the plume. As part of this process, the outer parts of the plume are effectively stripped off and form a suspension of sediment. Part of the plume will often reach the bed and then spread horizontally as a density current, mixing further with the surrounding water as it spreads and resuspending further sediment.

Depending on the nature of the bed material and the speed of the impact of the plume on the bed, it is possible for sediment to be mobilised from the bed and included in the plume.

The greater the initial density of the plume and the greater the release rate, the larger the proportion of released sediment which reaches the bed. Fast currents or high trailer dredging speeds and large water depth decrease the proportion reaching the bed. Methods that assume that all of the sediment released from a dredging operation is placed in suspension almost invariably gives rise to overestimates. Consideration of dynamic plume processes shows that an often significant proportion of the sediment is carried directly to the bed in close proximity to the dredger and does not contribute to the sediment plume, although it may subsequently be resuspended by currents or wave action.

# CALIBRATION

For the predictive techniques to be accepted they must be both as accurate as reasonably possible and demonstrated to be so. That means that there must be a concerted effort at good quality data collection. The authors believe that this is not an aim solely of VBKO and the Rijkswaterstaat but also of the dredging and regulating authorities in the USA. The protocols being currently developed should provide a basis for international agreement on what is required so that we can share each other's data as we seek to develop modelling capability.

The amount of data required is substantial. For example, if we consider 5 different types of dredging plant, 5 different classes of soil to be dredged, and 5 different sets of hydrodynamic conditions, this gives 125 dredging operations to be monitored. If we add other variables such as different operator skill levels, different types of drag head, grab etc, the size of the task begins to increase by a further order of magnitude. No doubt some significant progress can be made with the commitment of a few organisations but to achieve the ultimate goal requires international co-operation on a large scale.

## Protocols

A detailed review of published reports on sediment release from dredging operations revealed that field measurement methods were inconsistent and frequently failed to result in the collection of all of the data required to assess losses with different types of plant working in different soil and rock conditions. The inconsistencies prevent direct and meaningful comparison between the measurements and thus reduce their value. As a result of this work, it was decided that there is an urgent requirement for a set of standard field measurement protocols that can be used to provide calibration data for the predictive models.

Phase 2 of the VBKO project has therefore focused on the development of these protocols. Protocols have been developed for each of five dredger types, grab, cutter suction, bucket ladder, backhoe and trailing

suction hopper. It is self evident that the trailing suction hopper dredger is a special case because it is continuously moving. The protocols are described in Burt et al (2000).

Measurements undertaken for calibration purposes should preferably be made under near-ideal conditions in order to obtain as much high-quality data as possible. In some cases, the preferred measurement method defined in this protocol may not be practical. An alternative procedure has therefore been developed to overcome these difficulties.

The protocol is structured as follows:

- A working definition of sediment release based on the sediment flux related to the time after plume formation;
- General method of loss measurement;
- The characteristics of 'ideal' dredging sites which would be suitable for measurements purely for the purpose of obtaining calibration data;
- The equipment which is required to undertake the measurements in accordance with this protocol, the calibration of the equipment and its layout on the survey boat;
- Supporting data;
- The preferred method of measurement and the main procedures that must be followed in order to obtain accurate and consistent loss data. An alternative procedure which can be used when site conditions are not ideal is also presented;
- Data analysis procedures;
- Reporting requirements.

**First field trial of the protocols**

*The site*
The first trial was carried out on the River Tees, in the North East of England, with the co-operation of Tees and Hartlepool Port Authority. The dredging operation was a grab dredger carrying out maintenance dredging on the south side of the shipping channel. The dredger "Seal Sands" is a grab-hopper dredger belonging to the THPA. Maintenance dredging is carried out "in house". The measurements were carried out using THPA's buoy tender "Wilton". This had the distinct advantages of a large fore deck, overhanging straight bow and, with three independent $360^0$ propellers, the ability to move in a very controlled manner in any direction.

The detailed protocol for calibration measurements requires the selection of sites with the following main characteristics:

- areas of uniform water depth in which dredging can be undertaken for a period sufficiently long to determine the characteristic losses;
- areas of uniform materials;
- as far as is possible, unidirectional water currents;
- the absence of any structures against which the plume can flow and prevent clear-water to clear-water transects being undertaken.

The Tees trial site was located on the slope of the channel where water depths varied over very short distances. The materials which were dredged comprised firm to stiff bolder clays and soft sandy muds; it was extremely difficult to establish the relative proportions of these materials which were being dredged at any one time. The water currents were frequently markedly sheared due to saline stratification. Finally, the water depth on the north side of the channel sometimes prevented the Wilton from passing completely through the plume.

Thus, in almost every aspect, the site was less than ideal, leading to difficulty of plume quantification and interpretation of results. While disappointing in terms of calibration of the grab model, this simply (and valuably) confirms the requirements of the detailed protocol with respect to site characteristics.

*The Dredging Operation*
The measurement protocol requires very detailed records of the manner of operation of the dredger so that variation of the dredging method, and its effects on sediment release, can be investigated. The lack of a suitable positioning system on board the *Seal Sands*, and of adequate dredging depth instrumentation was disappointing. It prevented confident estimates of both the age of the plumes that were measured and analysis of the effects of dredging depth on sediment release.

Leaking hoppers are not entirely unknown in the dredging industry. In the case of this trial, it would have been useful to investigate the losses due to hopper leakage while no dredging was in progress, as it appears likely that the leaking hopper of the *Seal Sands* contributed to sediment losses. This requirement will be incorporated in the detailed measurement protocol.

The measurements suggested that erosion from the disturbed, freshly-dredged surface contributes significantly to the total amount of sediment in the plume. This contribution will obviously tend to increase as the size of the dredged area increases. The revised protocols will include a requirement to attempt to measure 'leakage' from freshly-dredged surfaces. This might be done by continuing to make observations for a period after dredging stops.

*Method of flux Measurement*
The trial clearly demonstrated that use of conventional profiling siltmeters can only work if the vessel from which they are deployed is able to move very slowly through the plume. In most cases, the plumes were only about 10-15 metres wide and several profiles are required in order to quantify the sediment flux. It is highly unlikely that future loss measurements will benefit from the availability of a vessel such as the *Wilton* and this factor alone mitigates against the use of profiling siltmeters (in conjunction with current measurements using an ADCP) as the main method of plume measurement.

The ADCP clearly demonstrated its ability to collect a substantial amount of data but, in this case, it appeared at first sight very possible that air bubbles may have corrupted the backscatter data. This was considered to be a potentially serious drawback to the studies because there does not appear to be any other method presently available that is capable of the high intensity and frequency of measurement needed to observe the plume in all of its dimensions. Because of this a series of additional tests were carried out on the Tees using the same dredger and observation equipment. In these experiments the dredger did not grab sediment from the river bed but simply filled the bucket with water then performed an otherwise normal cycle. At the time of preparing this paper the results of this work have not been fully written up but the evidence is clear that air bubbles are not the serious problem that was first thought. It was found that the attenuation of the signal strength by bubbles would have a greater effect than it actually did. The experiment gave valuable information on how old the plume had to be before the suspended solids concentration measurements could be reasonably relied upon.

As a result of this additional work the following conclusion can be made which will affect any future use of ADCP backscatter data to quantify plumes:

- unless there is relevant previous knowledge simple air bubble experiments should be undertaken prior to any ADCP measurements in order to establish whether or not there is a problem with air bubbles and to identify adjustments to the measurement procedure which may be required to minimise or avoid the effects of air bubbles;
- the very steep concentration gradients in young plumes mean that ADCP calibration must be undertaken at some distance form the dredger where the plume may be expected to be better mixed and

characterised by less steep concentration gradients; this in turn means that ADCP calibration must be undertaken separately from the actual plume measurements.

These requirements are being incorporated in the modified protocols.

*Speed of Measurement*
Measurements within each series of data appeared to be reasonably coherent: however, it is to be expected that the instantaneous rate of release will vary significantly and, with only 2 or 3 valid measurements in each series, it is not possible to determine if these are representative of the average. A far greater frequency of transects is clearly required. This requirement also militates against conventional techniques unless the total duration of the survey is greatly extended and site conditions are sufficiently uniform to permit extended periods of dredging at the same water depth and in the same materials. The former would have serious cost implications.

*General Conclusion about Measurement Methods*
The trial was successful in providing a clear demonstration of the difficulties of measurement. Overall it appears that the measurement for the purpose of model calibration of sediment flux away from the dredger can only be undertaken with reasonable speed and efficiency using acoustic techniques.
It has also been shown that a rapid rate of data collection (i.e. profiles across the plume) is required in order to facilitate an adequate quantification of sediment release and its variation.

**CO-OPERATION**
Following the Western Dredging Association Conference in June 2000 it became clear that both ERDC and HR Wallingford were working on the same problem, that is the measurement and modelling of sediment released into suspension during dredging operations. Meetings were held and it was agreed that there would be benefit to both parties in collaboration. The broad aim is to exchange information with a view to broadening the experience and knowledge base and avoid duplication of effort thus saving time and money for both parties.

In particular HR Wallingford provided copies of the draft monitoring protocols for ERDC to review. Comments were provided by a number of US reviewers from both ERDC and academia. Comments are now awaited from reviewers in:

- The Netherlands,
- The United Kingdom,
- Belgium,
- Denmark,
- France,
- Germany.

When all of the comments have been collated the protocols will be finalised.

There was an exchange of information on the modelling approaches being adopted by both parties. There appears to be little overlap and much to be gained by combining the two approaches. SSFATE developed by ERDC is equipped with high quality plume visualisation whereas TASS has so far focussed on the source term of turbidity generation. The present version of SSFATE requires this to be specified as input rather than predicting it from more basic input parameters.

At the six monthly meetings, alternating between the US and Europe, information has been exchanged about proposed monitoring exercises. Data is also being exchanged from completed exercises.

## CONCLUDING REMARKS

With increasing pressure to identify and control the effects of turbidity caused by dredging it has become necessary to improve the knowledge of actual effects, leading to the ability to predict them. The first stage of the work carried out in Europe that is reported here has been to attempt to model the rate of sediment release. Plume models exist and have the potential to be refined but without knowledge of the source term they are of limited value.

Prediction of the source term requires a good understanding of the processes that take place during the dredging of a material. In most cases the processes are not steady state but vary according to a whole range of parameters. This in turn means that it is essential to obtain calibration data from field measurements. Those who have attempted to obtain even a single set of measurements of a dredge plume will testify to the complexity and difficulty of the task. For this reason the European team has been developing protocols for the collection of data. These are in process of international review, including the US. The first field trial has taken place using a grab dredger and has resulted in changes to the protocol based on lessons learned. The next is planned to take place later in 2002 using a trailing suction hopper dredger, where the problems increase not least because the dredger itself is also moving.

The co-operation agreement between ERDC and HR Wallingford is providing a basis for the exchange of ideas and understanding of the processes involved and is providing access to data available on both sides of the Atlantic Ocean. It is hoped that future co-operation may lead to the eventual production of predictive software that can be trusted by engineers and regulators alike. Even when that is achieved there will still be a need to know what the environmental effect of the turbidity is, but at least we will have achieved one major step in addressing the problem.

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# *Appendix 3*

US-UK Cooperation on Dredging Turbidity Modeling

# Appendix 3  US-UK Cooperation on dredging turbidity modeling

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**Abstract**
The authors and their respective organizations have been independently working towards developing models to predict turbidity generation by dredges. Through a cooperative arrangement, the authors are working toward a common set of predictive methodologies and software tools. Both parties and the dredging community should benefit from collaborative rather than independent efforts. This paper reflects the status of this cooperative effort between HR Wallingford and the University of Utah. It discusses the current state of dredging turbidity modeling and describes the efforts and research necessary so that better models are available within a few years. Existing models are critically evaluated with a focus toward developing a unified strategy for the next generation of improved versions. With only limited resources available to support this effort and a strong demand for the results, both parties feel it is crucial to join forces and minimize redundancy.

**Keywords**: plume, transport model, contaminant fate, dredging windows, contaminated sediment.

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## INTRODUCTION

Environmental impacts associated with dredging operations have been an issue for decades. Current concerns seem to focus on two distinct areas: a) impacts of water quality degradation on fish and b) transport and redeposition of toxic constituents. Prior research has provided useful information on the levels and extent of water quality impacts under a narrow range of conditions. Funding constraints have forced prior research efforts to focus almost exclusively on the behavior of solids resuspended by the dredging operations, assuming that the contaminants of concern – typically hydrophobic in nature- behave in a similar manner.

Concerns over fish impacts are associated with both conventional and toxic constituents. Dredging windows, defined as a period during which dredging may take place within a defined area, are largely set based upon a perception of potential impacts associated with turbidity plumes and potential sediment deposition. Turbidity plumes represent potential barriers to natural fish migration and movement, due to both reduced visibility and the potential for less desirable water quality conditions such as reduced dissolved oxygen concentrations and increased ammonia concentrations. In the absence of definitive information, regulatory authorities set standards for sediment release or otherwise restrict dredging operations to a potentially unnecessary degree. Those responsible for protecting and enhancing fish populations in the US implement conservative dredging windows. In many areas of the US, these windows have now become so narrow that they jeopardize commercial navigation. Increased knowledge about environmental impacts resulting from dredging operations should either justify existing dredging windows or allow dredging windows to be increased if it shown that impacts are acceptable over a longer time period with a reasonable degree of certainty. In other cases it might be appropriate to further restrict dredging activities unless additional controls can be implemented that mitigate impacts.

Sediments contaminated with toxic substances raise additional concerns, depending upon the environment and conditions in which they exist. They primarily include increased exposure and consumption of toxic substances by humans, fish and other biota, potential for resuspended contamination to resettle leaving contamination spread over previously dredged and previously unimpacted areas, and the potential effectiveness of dredging as a remedial tool.

Regardless of the specific contaminant or environmental impact of concern, the lack of definitive data and predictive tools to make reliable a priori estimates of environmental impacts that will be associated with specific dredging projects hamper economic and environmental progress in waterways and waterbodies throughout the world. Significantly improving our predictive capability will require a substantial, wide-scoped, multi-disciplinary research initiative. This paper identifies the primary components of that research initiative, the status of research related to each component, and a general description of tasks necessary to reach critical levels of competency. This document does not consider potential funding sources or funding mechanisms that may be necessary to successfully complete this research.

## PREVIOUS STUDIES

Developing a research framework for water quality impacts resulting from dredging operations is not a novel idea. John et al. (2000) provides a structured framework for assessing potential environmental impacts associated with dredging-induced turbidity plumes for a specific project. The CIRIA framework serves as a useful starting point. Even though it is primarily aimed at making decisions on dredging projects, it lists what needs to be known and indicates areas where knowledge is lacking.

The National Research Council has issued a series of reports that indirectly addresses turbidity associated impacts during dredging operations. NRC (1997) and NRC (2002b) address water quality impacts as they relate to contaminated sediment management. NRC (2002a) addresses ecological concerns that lead to dredging windows stemming from turbidity itself and subsequent deposition. All three NRC reports note the need for extensive research to develop reliable predictive methods for estimating water quality impacts during dredging operations.

## DEFINING PHASES OF PLUME DEVELOPMENT AND DECAY

### Plume Development

In an ideal world it would be possible to measure the rate of release of sediment at exactly the location(s) where it is released. However, with the exception of the overflow from trailer dredgers, it is not possible to do this for both practical and safety reasons. In addition, both conventional turbidity meters and acoustic measurements of suspended sediment are subject to errors when air bubbles are entrained in the water column, as is almost invariably the case close to dredging equipment.

Even if it were possible to undertake such measurements, they may be of little practical use when estimating the potential impacts of dredging. In most cases, these impacts are assessed on the basis of the results of numerical modeling of sediment transport away from the dredging site. With most types of dredger, the release of material at the source(s) includes relatively large lumps of material that descend almost immediately to the bed. These certainly do not impact on the sediment regime beyond the immediate area of the dredging. However, it is noted that such material (having being weakened during the dredging process) may contribute by other processes to the overall sediment transport from the dredging area and may also be important in the context of assessing the impacts of contaminated materials.

An additional complicating factor arises from the very turbulent zone in the immediate vicinity of the dredging equipment. Movement of cutterheads and cutter ladders, grabs, buckets and trailer dragheads creates significant artificial turbulence that initially hinders the settling of all but the largest particles. The size of this zone is in most cases likely to be small, perhaps of the order of a few metres around the moving equipment. The duration of this phase of plume development is short and is measured in seconds.

As released sediment moves out of this turbulent zone by water currents (or the dredging equipment moves away), the behavior of the remaining sediment in suspension (ie. excluding the large lumps) becomes more predictable and easier to model. For these reasons, two ‘sources’ of sediment release have been defined: the True Source and the Practical Source.

The True Source is the actual location where sediment becomes detached from the dredging equipment. It is in an area of high turbulence where the processes of plume development are dominated by ‘fall out’ of large sediment lumps, removal of rapidly settling particles, and possibly even hindered settling of some particles. This area is defined as the Dredging Zone.

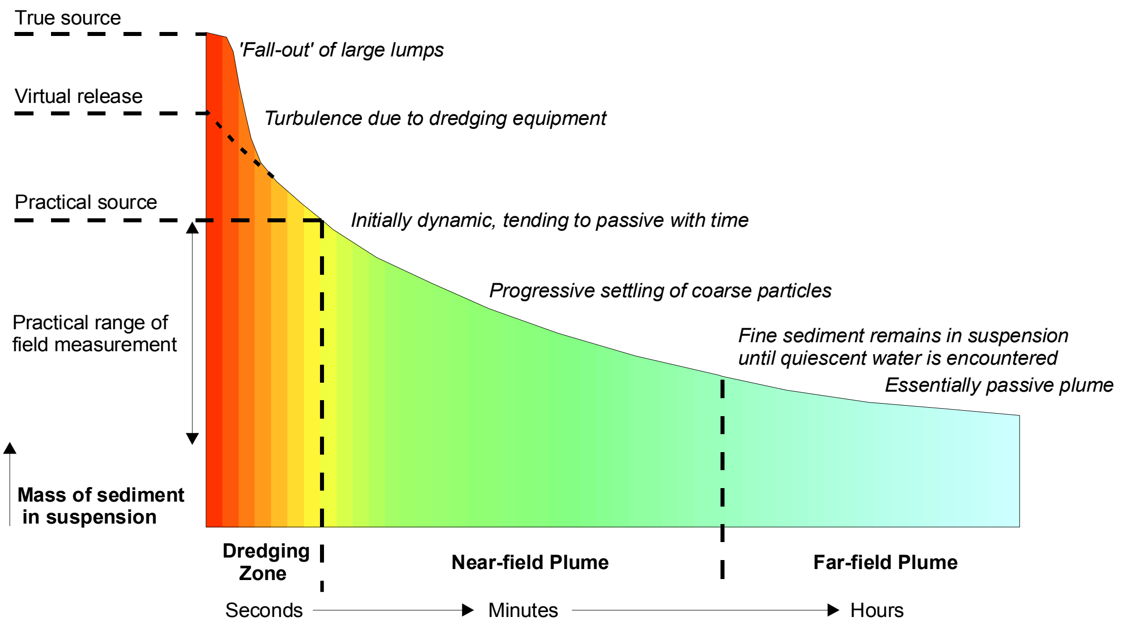


**Figure 1. Stages and processes of plume development**

The Practical Source lies at the edge of the dredging zone. This point, in some cases, may be approximately coincident with the closest point to the dredger at which meaningful measurements can be made. More importantly, it is the point at which subsequent plume behavior becomes reasonably predictable and quantifiable.

The stages of plume development are schematically illustrated in Figure 1. Over a timescale of seconds, and a distance of a few metres, the plume passes from the Dredging Zone into the Near Field. The material remaining in suspension is advected away from the dredger by the ambient current and it becomes possible to describe the elongating cloud of suspended material as a plume.

In almost all cases, the material that passes from the dredging zone into the near field will comprise a continuum of particle sizes ranging from lumps that were too small to overcome the turbulence within the dredging zone, to sands, silts and clays. Three processes will then act, in combination, on the suspension:

1. the plume will initially behave in a dynamic manner and will settle as a whole towards the bed as a dense liquid at a speed that is determined by its size and density contrast with the ambient water; this initial descent speed may be orders of magnitude faster than the theoretical settling speed of the individual finer particles contained in the suspension;
2. differential settlement will take place within the suspension, with the coarser particles settling faster than the finer particles;
3. water currents, if present, will advect the suspension away from the dredging site.

Dynamic plumes are most commonly associated with high-volume, high-concentration overflow release from trailers but it is the case that most plumes are initially characterized by some degree of dynamic behavior. The TASS models incorporate a dynamic plume module.

Even when the plume behaves dynamically, differential settlement will be an important mechanism of development. Coarse sand with a diameter of 2mm will settle at about 300mm/s. At the other end of the sand-size spectrum, the finest sand (0.063mm) will settle at about 3mm/s. In 15 m of water moving at 0.5m/s very fine sand introduced at the water surface will take about 1.5 hours to settle and will travel about 2.5km before reaching the bed. Very coarse sand will take 50 sec to settle and will travel only 25m. Disaggregated mud in suspension (at any concentration) in the same circumstances will not settle to the bed. The water velocity has to be below about 0.1m/s in the near bed zone for any settlement to take place.

The near-field phase of plume development can therefore be summarized as the period in which an initially dynamic plume loses its momentum as differential settlement, assisted by turbulent diffusion, acts to reduce its excess density. Coarse particles and faster settling fine particles will progressively settle out of suspension, leaving only the fine particles to form a passive plume. The duration of this near-field stage of plume development will vary considerably depending mainly on the initial concentration and size distribution of the particles in the suspension, the volume of the suspensions, water depth and magnitude of the normal hydraulic turbulence that takes place in moving water. In most cases, it is likely to be complete within a period of tens of minutes but perhaps as much as 1 to 1.5 hours.

The Far-Field Plume is essentially passive and comprises a dilute suspension of fine sediments. The term "far field" is most commonly used in the context of the fate of the fine fraction of the material and the limits of potential environmental effects. The path taken by the plume and the solids suspended in it are determined by the site-specific hydrodynamics. These may be unidirectional as in the case of canals or variable and oscillatory in the case of coastal waters or estuaries. It is beyond the scope of this document to describe these. Many computer models exist that are capable of providing the necessary hydrodynamic background to plume evolution.

There is no clear boundary between Near Field Plume and Far Field Plume. The one that is implied here is that only the finest particles remain in the far-field. Suspended sediments in the near-field may settle at different rates.

**Defining sediment release**
It is clear from the above that the various processes affecting the movement of sediment from the original (true) source do not occur in discrete packages and that the particle size distribution of the released material varies significantly over time. The entire process may be described as a continuum. Thus, any definition of sediment release rate will be somewhat arbitrary.

One alternative is to devise a definition that is appropriate for input to plume models. For near-field models, or when near-field modeling is an integral part of far field modeling, the description of the "source" must include:

1. the location of the source;
2. the flux of sediment at that point;
3. the particle size distribution (or more directly the settling velocity distribution) of suspended sediment at that point.

From the particle size distribution (or settling velocity distribution) it may be theoretically possible to continuously calculate the settling rates and to derive the type of curve shown in Figure 1. However, the first few seconds, when large lumps are falling out of suspension, would be difficult to simulate because the particle size distribution of all the material released at the true source is almost impossible to establish by measurement.

An alternative approach is to fit a curve to the measured decay of the flux in the near-field and to extrapolate back to the theoretical location of the True Source (zero on the x axis of Figure 1). This computed release rate can then be defined as the Virtual Release Rate. Whilst this would have mathematical relevance as input to a plume model it would not necessarily represent what was happening at this location. However, it should only be used if the plume model properly represents sediment settling rates across the particle size spectrum otherwise it would lead to an overestimate of advection into the far field.

**Terminology**
The above discussion leads to a set of definitions that are useful for future discussions regarding turbidity plume modeling. Table 1 defines useful terms for future discussions. These terms have been adopted by the TASS project.

**Additional Considerations**
Other factors also influence the extent and duration of water quality impacts during dredging operations. Transport barriers substantially modify flow regimes and, subsequently, transport. They are used ubiquitously around dredging operations in sensitive areas. However, little information is available to definitively quantify the value of transport barriers. Similarly, there is extensive controversy about contaminant release that may be associated with dredging activities, particularly at sites with high concentrations of anthropogenic constituents. Lastly, the prospect that dredging operations typically leave behind some sediments that were previously in the dredging matrix has raised considerable concern for remedial dredging operations. This section discusses the state of knowledge and research issues associated with each.

**Table 1. Useful terminology and definitions for discussing turbidity plume and contaminant transport modeling during dredging operation.**

| | |
|---|---|
| True Source | Location(s) of the active part(s) of the dredging unit from which sediment is released. |
| True Release Rate | The rate at which sediment is released at the True Source (not directly measurable). |
| Dredging Zone | The zone immediately below and adjacent to the active dredging unit where the material is subjected to mechanically induced turbulence. Large lumps and coarse material settle to bed through clouds of finer suspended material. |
| Practical Source | The boundary between the Dredging Zone and the Near-Field Plume. In practice, this is likely to be the nearest point to the active unit where it is possible to obtain meaningful and relevant measurements. Its location relative to the true source must be known. |
| Practical Release Rate | The rate at which sediment passes out of the Dredging Zone. |
| Near-field Plume | The stage of plume development in which the coarser fraction of suspended sediment settles to the bed whilst being advected by the ambient currents; the initial stages may be dynamic but the plume becomes more passive with time. |
| Virtual Release Rate | The estimated Release Rate that is back-calculated from the decay curve of the Near-Field Plume. |
| Far-field Plume | The stage of plume development in which only the fine fraction remains in suspension and is capable of being advected over long distances by the ambient currents as long as the velocity of that current remains above a critical threshold. |
| Age of Plume | The time that has passed since the sediment first entered the water column at the true source. |

**Transport Barriers**
Silt curtains and silt screens are commonly used on dredging projects where water quality impacts are a concern and the environment allows. Some environmental dredging projects construct barriers using sheet pile or other materials to impede transport of suspended sediment and contaminants away from the dredging site.

The placement and success of transport barriers can vary substantially from site to site. Silt curtains and silt screens are particularly difficult to deploy and almost impossible to maintain in open water subject to strong currents, significant wind, or large waves. They also can impede traffic to and from the dredge that provide fuel, supplies, and crew necessary to keep the operation going. Some have deployed silt screens close to stationary dredging operations (e.g. bucket dredges) to retard transport away from the source while not impeding traffic. However, unless the dredging platform is appropriately designed, the continual movement of the silt screens makes this difficult.

Regardless of the transport barrier and its deployment, it is important to fully assess its water quality benefits to determine if the effort and cost required are justified.

**Contaminant Release Mechanisms**
Contaminants associated with bottom sediments are absorbed onto the sediment particles and exist in the pore water in dissolved form. Since most sediment contaminants are hydrophobic, the majority of the in situ contaminant mass is usually associated with sediment particles. The actual distribution is site-specific depending upon the environmental conditions, sediment characteristics, and contaminant properties. Since

the sediments have typically been in place for some time, contaminant partitioning is usually at or very near equilibrium.

Contaminants in both phases, particulate and dissolved, are released to the water column as sediments are disturbed. Even though the initial dissolved contaminant mass contributed from the porewater may be low, dissolved contaminant concentration increases as particulate-bound contaminants attempt to reach equilibrium in their new, more dilute environment. The fate of dissolved and particulate contaminants is of interest because both provide potential pathways of contaminant loss. Particulate contaminants potentially spread the contamination over a larger area and continue to provide a source for dissolved contaminant loss. Dissolved contaminants are subject to volatilization as well as being readily available to fish and other biota.

**Post-dredging Residual Sediments**

A number of recent contaminated dredging projects have noted a veneer of sediments above the cut-line that exhibit contaminant concentrations consistent with sediment targeted for dredging. These "residual" sediments may assist in the rapid reestablishment of biological communities that existed prior to dredging. However, they can pose a substantial problem when contaminants are present. Their presence as surface sediments with a significant contaminant concentration may pose a continued risk to the biological community. Further, these residual sediments tend to exist in a very dilute form, often exhibiting fluid-like behavior. As such, they may be more susceptible to erosion and transport than surface sediments prior to dredging.

Residual sediments have only become known in the past few years. Little, if any, research has been conducted to quantify the sediment volume or contaminant mass that may exist as residual sediments. No information on the mechanisms of residual sediment generation is available.

The deposition of resuspended sediments likely contributes little to sediment residuals in the dredging area. They are included in this framework because of potential impacts associated with post-dredging erosion of these soft sediments. Deposition of resuspended sediments outside the dredging area is a substantial concern and is also considered in this research framework.

**RESEARCH NEEDS**

The preceding discussion summarized the current state of knowledge related to turbidity. Table 2 presents the authors' qualitative assessment of dredging water quality impacts and available predictive methodologies.

This section describes research necessary to develop the capability to produce such assessments. It is assumed that the final product of this research is a collection of algorithms that would be implemented through a series of software tools.

**Loss Mechanisms**

Identifying and understanding the mechanisms through which sediments and contaminants are introduced into the water column by dredging operations are crucial to developing effective operational and mechanical control measures. For some dredges, some of these mechanisms are obvious and have been identified by multiple researchers, e.g. bucket dredge. The mechanisms are less well understood for dredges with more complex operations. Cutterhead suction and hopper draghead dredges are examples, although some researchers have postulated mechanisms and even initiated mechanistic source models based upon these hypotheses.

This requires combining field and laboratory investigations with mathematical modeling to understand the loss mechanisms and establish mechanistic source models to estimate losses to the water column. The mechanics and operation of every dredge type are different and dictate release mechanisms. Equipment modifications such as a different style bucket or draghead may also change release mechanisms and the

rate of release. Thus, as many dredge types as possible need to be addressed directly while establishing a protocol for developing source models for other dredge types or variations that may come along.

Dredging operations are unable to capture and remove all sediment loosened by the dredge. Some sediment returns quickly to rest on the bottom; this sediment remains at a relatively high density. Other sediments create a dilute suspension in the immediate vicinity of the dredging operation. In mass terms, this is typically a small number, but the water quality impacts can be substantial. Suspended sediment modeling is often perceived as the simple component of dredging related water quality impacts. However, sediments in this area experience a wide range of conditions and exhibit a similarly wide range of settling properties.

**Table 2. Summary of current knowledge and required research efforts.**

| | | Loss Mechanisms | Dredging Zone | Near-field Zone | Far-field Zone | Residual Sediments |
|---|---|---|---|---|---|---|
| Fate & Transport | TSS | 2-3 | 0-2 | 1-3 | 3-4 | 0-1 |
| | Contaminants | 2-3 | 0-1 | 1-2 | 2-3 | 0-1 |
| | Model Development | 0-1 | 0-1 | 2-3 | 4 | 0-1 |
| Ecological Impacts | TSS | NA | 0-1 | 1-3 | 1-3 | 0-1 |
| | Contaminants | NA | 0-1 | 1-2 | 2 | 0-1 |
| | Model Development | NA | 0-1 | 2 | 2 | 0-1 |

Rating system:

0 – no significant knowledge or prior work exists

1 – preliminary research available; initial development underway

2 – research progressing, extensive work remains

3 – modest available research results available; reasonable understanding of processes/requirements exist

4 – research mature, but available models lack dredging context

5 – research mature; models complete

A series of laboratory tests, both bench-scale and prototype, are required to fully characterize those mechanisms of sediment loss not yet fully understood. These experiments should provide a solid basis upon which to develop mathematical models of TSS generation processes.

Contaminants are released to the water column during dredging in two forms: a) absorbed onto sediment particles and b) directly from porewater. The total contaminant mass contributed from the porewater is thought to be small, but requires careful evaluation. Contaminant adsorption and desorption is a complex process, not fully understood, even though equilibrium partitioning theory is widely accepted. DiGiano et al (1993) tested an elutriate procedure for estimating sediment-bound PCB redistribution from New

Bedford Harbor sediments after being resuspended into the water column. They concluded that the procedure provided reasonable results, but not necessarily better than traditional equilibrium partitioning. Further work is required to further refine the procedure and test its value at additional sites and for different contaminants.

Adsorption kinetics are also important to estimating contaminant release to the water column since most resuspended sediment resettle to the bottom in the vicinity of the dredging operation. Unfortunately, the science of adsorption-desorption processes and kinetics is not sufficiently developed to support reliable non-equilibrium partitioning computations. Laboratory testing will be required to advance this science.

Suspended sediment and contaminant loss processes associated with dredging operations are complex. Many of these will not be directly measurable. Neither field nor laboratory tests will be able to fully quantify the complete array of processes. Thus, it will be necessary to utilize computer models of dredging operations to extend available data to a wider range of conditions.

This will require the development of multiple source/loss models ranging from simple, easy to apply screening level models to complex, multi-dimensional, transient models of dredging operations. It is expected that the screening level models would be sufficient for most cases, but their development will require more complex real-time operation models to fully understand loss mechanisms and gather enough calibration data to develop reliable screening-level source models.

**TSS Fate and Transport**

A variety of existing suspended sediment transport models are capable of predicting downstream suspended sediment transport resulting from dredging operations. However, since the models are generic, their dredging related context is often not clear. Most potential users need guidance to determine the dimensional complexity required for their application. Moreover, a comprehensive modeling approach would likely involve different levels of dimensional complexity for different regions of the plume.

Each model also has a specific method of inputting the source geometry and resuspension rate. Since these models were mostly developed with other types of sources in mind or to model suspended sediment concentrations from one point to another, the terminology used in the interfaces and User's Manuals does not immediately translate to dredging operations.

Further complicating matters is that most water quality modeling applications involve extensive calibration of existing conditions prior to being applied to various forecast scenarios. Since suspended sediment models contain multiple turbulent diffusion coefficients and settling rates that are difficult to quantify, these are often treated as calibration parameters and adjusted within "reasonable" ranges until a model reflects the calibration data within an acceptable degree of accuracy. This practice is not acceptable for dredging operations because the conditions being modeled do not exist prior to the commencement of dredging in that area. Settling rates are particularly problematic because sediments resuspended by the dredging operation are those that preferentially settled in the area previously, suggesting that their settling rate is likely different from typical ambient suspended sediment particles. Further, the historical conditions under which they settled is unknown and may have been atypical.

All of these combine to make it difficult for the typical user to select the appropriate suite of tools necessary to achieve their desired result, then apply them to a specific dredging operation in a manner that produces reliable results. Thus, the research focus must be to (1) produce a series of protocols that source models can utilize to output source geometry and strength, (2) develop guidance for transport model selection and utilization, and (3) develop predictive methods upon which to base reliable parameter estimates for those typically calibrated. Requirements that are more specific are addressed below.

Localized currents induced by dredge movement, suction inlets, and other dredging actions influence mixing and transport in the immediate vicinity of the dredging operation, referred to in Figure 1 as the Dredging Zone. Thus, considerable attention to hydrodynamics associated with dredge operations will be

required to develop a solid basis for TSS transport within and out of this zone. Dredge-specific physical and mathematical hydrodynamic models are necessary to identify important dredge-specific operational parameters and understand their influence on sediment resuspension and loss processes.

TSS that escapes the Dredging Zone enters a more quiescent environment with predictable currents. Suspended sediment in the Near-field Zone, however, is likely to experience considerable concentration changes due to extensive flocculation and settling. Methodologies need to be developed that allow accurate prediction of TSS concentration within the first few meters of the dredging operation. Je (1998) proposed a combined laboratory and modeling approach for site-specific TSS transport modeling resulting from dredging operations. This approach or a more appropriate approach must be validated.

Suspended sediment transported beyond the near-field zone into the far-field zone exhibits characteristics more similar to ambient suspended solids. Concentration changes are not as rapid as in the near-field zone and existing modeling approaches are generally applicable to transport in this region.

Sediments resuspended by dredging operations eventually redeposit on existing bottom sediments. Extensive sediment deposition may smother bottom organisms; the potential spread of absorbed contaminants is also a concern. Thus, deposition patterns are of considerable ecological and environmental interest. Modeling of suspended sediment transport in all zones must be coupled with predictions of spatial deposition patterns and estimates of sediment density and quality.

**Contaminant Fate and Transport**

The origin, fate, and transport of water quality constituents other than suspended sediment during dredging operations continue to be controversial. Much of the controversy results from areas in which the available chemo-dynamic information is inadequate or the operation of the dredge makes the situation too complicated for a complete analysis. A significant research focus is required to resolve these issues for both toxic and conventional constituents (e.g. ammonia).

Much of the uncertainty about contaminant fate and transport is associated with sediment disturbances in the dredging zone. The release of dissolved contaminant mass from porewater and from sediments suspended only shortly before resettling in the immediate vicinity of their original position have both been suggested as significant sources of contaminant loss. Intensive research will be required to quantify the impacts of these phenomena on overall contaminant fate and transport.

Contaminant fate and transport in the near-field zone are thought to be dominated by the flocculation and settling of suspended solids and dispersion-related dilution of dissolved contaminant concentrations. Contaminant redistribution between the absorbed and dissolved phase occurs as hydrophobic constituents attempt to reach equilibrium in their new environment. Since this transport only lasts minutes, equilibrium partitioning is probably inappropriate for most environments. However, the extent of contaminant release in the near-field zone is an important component of contaminant fate and transport modeling. Laboratory studies will be required to investigate the kinetics of partitioning as suspended sediment concentrations change in the near field.

Existing contaminant transport models are generally capable of predicting far-field contaminant transport. However, some effort will be required to verify their capabilities in downstream transport regions. The most significant concern is the applicability of equilibrium partitioning and the influence of particulate characteristics on contaminant adsorption-desorption.

Like sediments, contaminants are redistributed during dredging operations. The extent of the redistribution and final resting place of the contaminants are crucial information. Models and procedures for contaminant fate and transport must be able to reliably predict these parameters.

**Ecological Impacts**
The integrating factor in the above discussions is the protection of ecological resources, although human health is certainly an equivalent concern. While the general focus of this research framework is the development of methods to estimate water quality changes due to dredging operations, it is important to develop methods to assess the impacts of these changes on the resources that are being protected.

The extent to which turbidity and suspended sediment impact fish behavior and the amount of resulting deposition are crucial to the proper establishment of dredging restrictions that protect ecological resources. Without reliable methods to estimate these impacts, dredging restrictions will necessarily be overly restrictive, increasing the difficulty and cost of channel maintenance.

Contaminants in the water column are available for direct ingestion by fish and other aquatic organisms. Since dredging operations increase contaminant concentrations in the water column, contaminant ingestion and uptake is also almost certainly increased.

**Summary of research needs**
*Development of an internationally accepted monitoring protocol*
There is a need to be able to comprehensively describe the turbidity plume. This means improving the quality of the baseline data and improving modeling techniques.

*Field testing ADCPs*
Field tests should be carried out to investigate and demonstrate the viability of using ADCP alongside more conventional techniques to adequately measure suspended solids concentration.

*Determine a standard procedure for measuring or interpreting relevant soil properties*
This recommendation of the CIRIA report was later researched under the VBKO project. A review suggested that there was a need for a more scientific approach and further work has been done on the dredger/soil interaction, with particular regard to draghead generated plumes. More research on this is needed.

*Monitoring benthic boundary layer processes*
Although ADCPs are widely used to monitor sediment plumes, they miss crucial parts of the water column, namely the 10 per cent nearest the seabed and the surface layers. These areas are likely to be the most important in terms of biological activity and therefore the areas where biological impacts are most likely to occur.

*Monitoring real environmental effects*
There is a general lack of field data regarding the environmental effects of dredging induced sediment plumes. Therefore, targeted field surveys are required in order to determine whether (predicted) impacts arising from sediment plumes are accurate and to quantify their significance.

*Filling gaps in modelling capability*
Recommendations for the development and refinement of relevant models are discussed below. The next stage will be to use the field and laboratory data obtained to refine existing models.

*Source term*
New models to predict source terms are already in existence but lack calibration data. It is clear that significantly larger gains can now be made through calibrating the models available based on good data, rather than refining the models themselves. The data obtained will provide a means of determining coefficients in the algorithms used in those models and will perhaps highlight the need to include other parameters.

*Plume dispersion*
Several models exist which can be and are used for applied modeling of plume advection and dispersion. The modeling techniques have become well established but good calibration data is still sparse.

*Cohesive sediment modelling*
Cohesive sediment modeling represents an area where the development of models would be beneficial, in particular, model development concerned with the behavior of concentrated suspensions and the related formation of fluid mud. This is presently one of the subjects of a major European research project.

*Water quality models*
Models also exist which can be and are used for the prediction of water quality impacts. However, these models do not reproduce the dynamic interaction of contaminants with water and sediment. Instead, they take a simpler approach to processing dispersion model results.

*Model robustness*
Models should be calibrated or validated with observations from the dredge site and clear guidance given on whether the models in use are site-specific or generic. Modeling must also be appropriate to the hydrodynamic and bathymetric environment in question.

In summary, it is recommended that, as a priority, calibration data are obtained from field measurements and used to upgrade existing computer models of source terms. Furthermore, the collection of these data must be based on a recognized, adopted measurement protocol.

## CONCLUSIONS

Turbidity plumes and resulting water quality impacts associated with dredging operations are of considerable interest in many projects. The lack of defensible data and proven modeling methods impair sound management and regulatory decisions. Extensive research is needed to improve the current state of knowledge. The research needs identified in this paper and the more detailed review that is in preparation will provide a basis for a structured and prioritised programme with clearly defined objectives.

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